Title: Nuclear physics for multimessengers

Date: Dec 13, 2018 01:00 PM

URL: http://pirsa.org/18120024

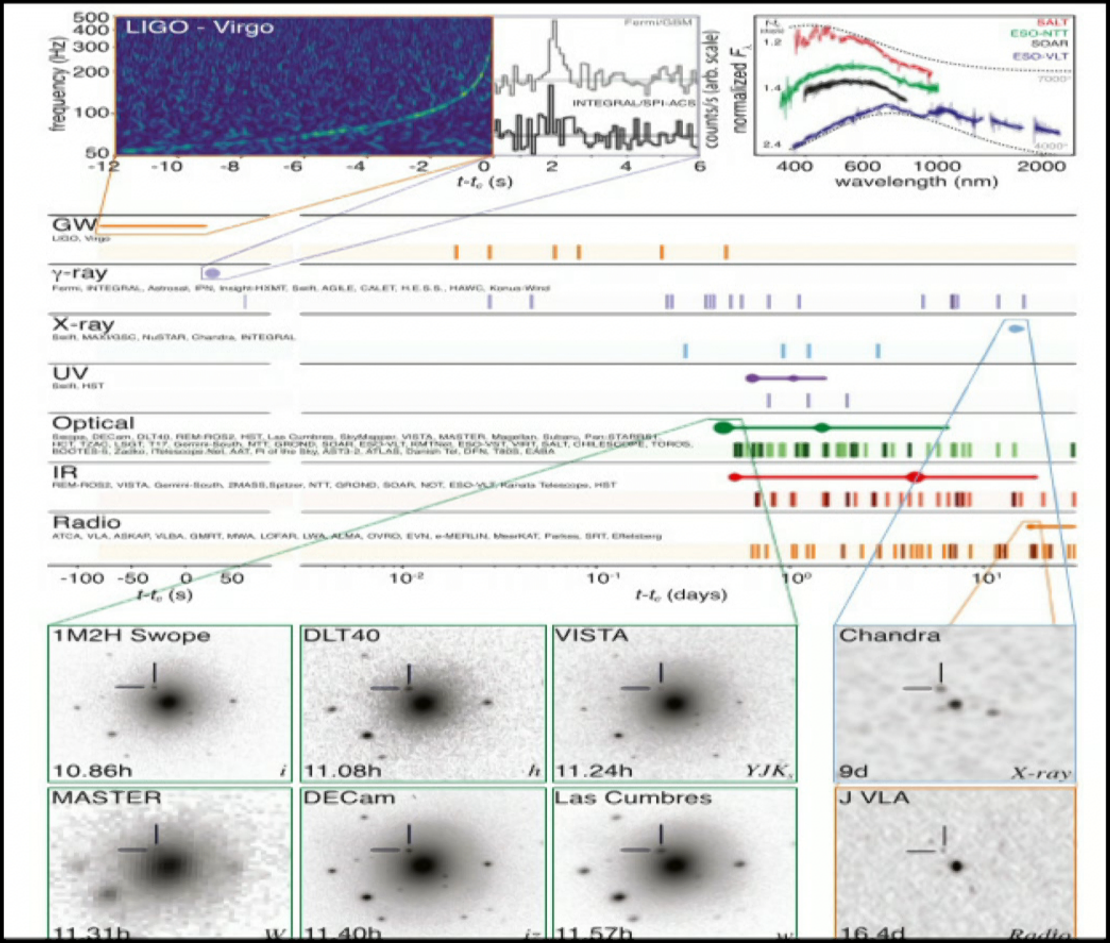
Abstract: <p>Over the last few years gravitational wave (GW) detections have marked
the beginning of a new era of astrophysical observations. When the
emitters include a compact object like a neutron star, the GW signal
is accompanied by emissions in different bands, e.g. X-rays,
gamma-rays, optical and neutrinos. The interpretation of such
multimessenger signals allows us to gain a deeper understanding of the
interiors of compact objects. One main challenge is to link our
knowledge of nuclear interactions to macroscopic properties of dense
objects in the Universe. In this talk I will discuss selected aspects
along the interface of nuclear physics and astrophysics</p>

Nuclear Physics for Multi-messengers

Liliana Caballero
University of Guelph

Strong Gravity Seminar
Perimeter Institute
December 13th 2018

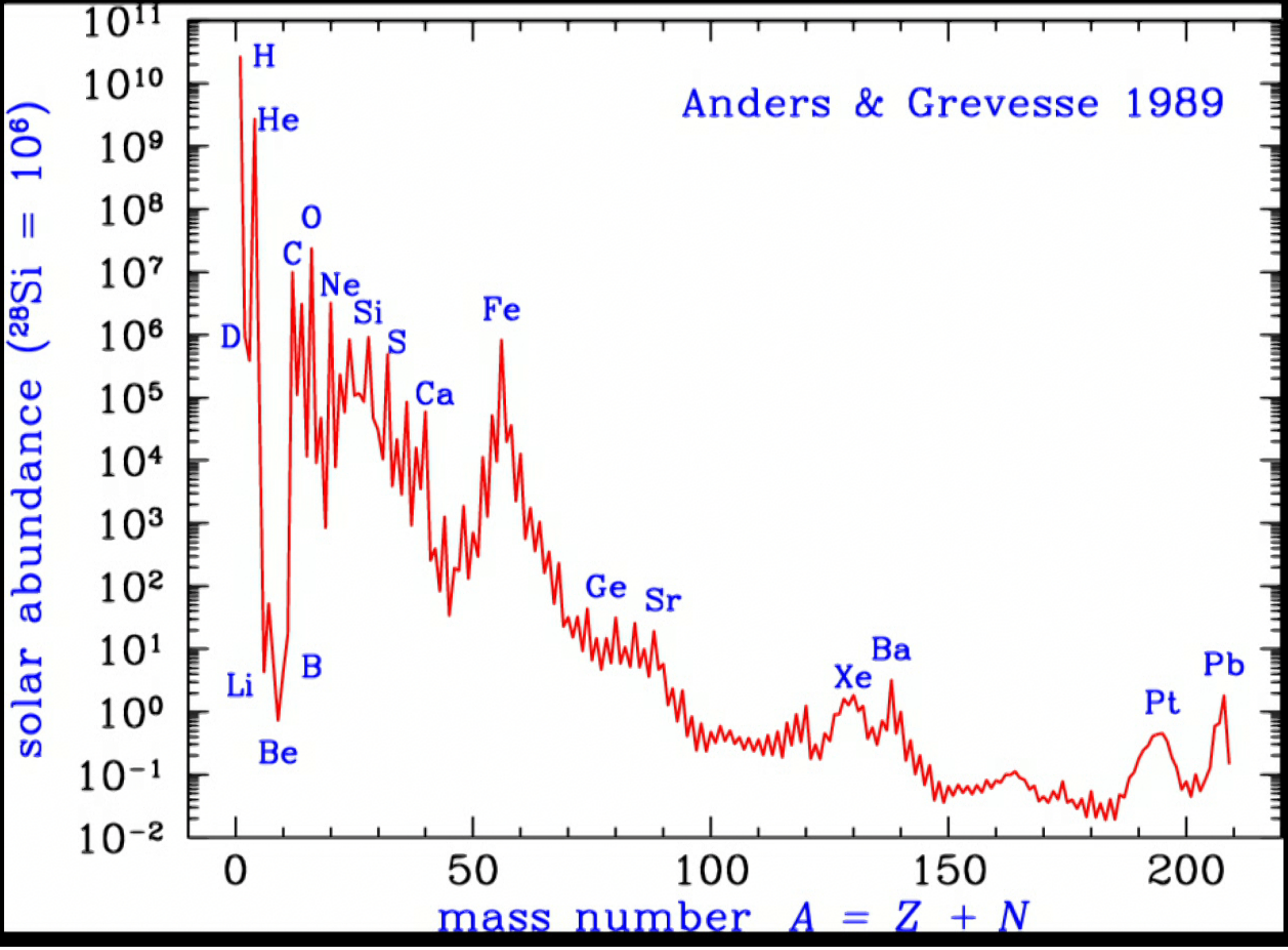
Multi-messenger era!

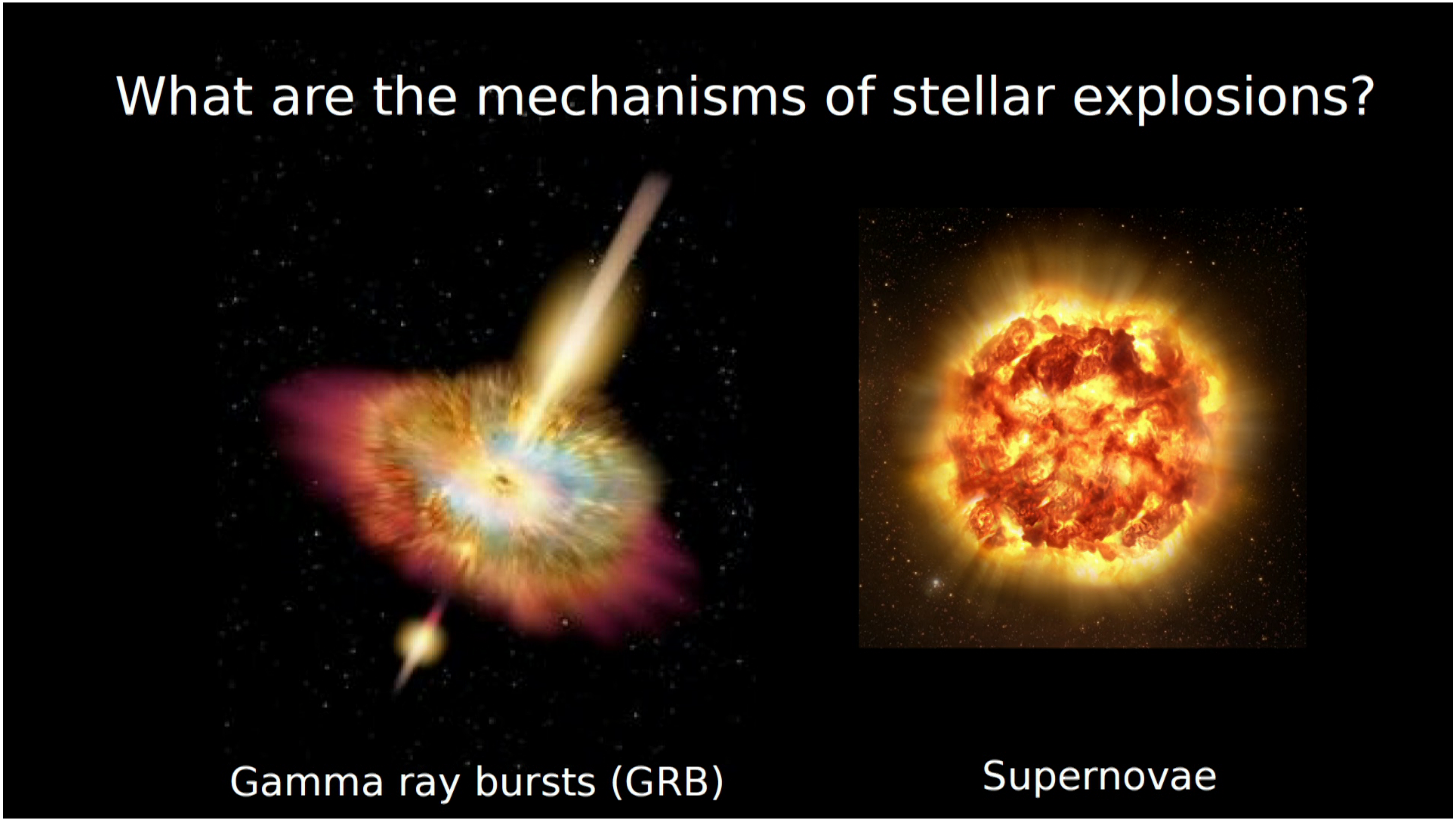


LIGO Collaboration, PRL 2017

ApJ Letters 848 2017

How and where are the heavy elements made?

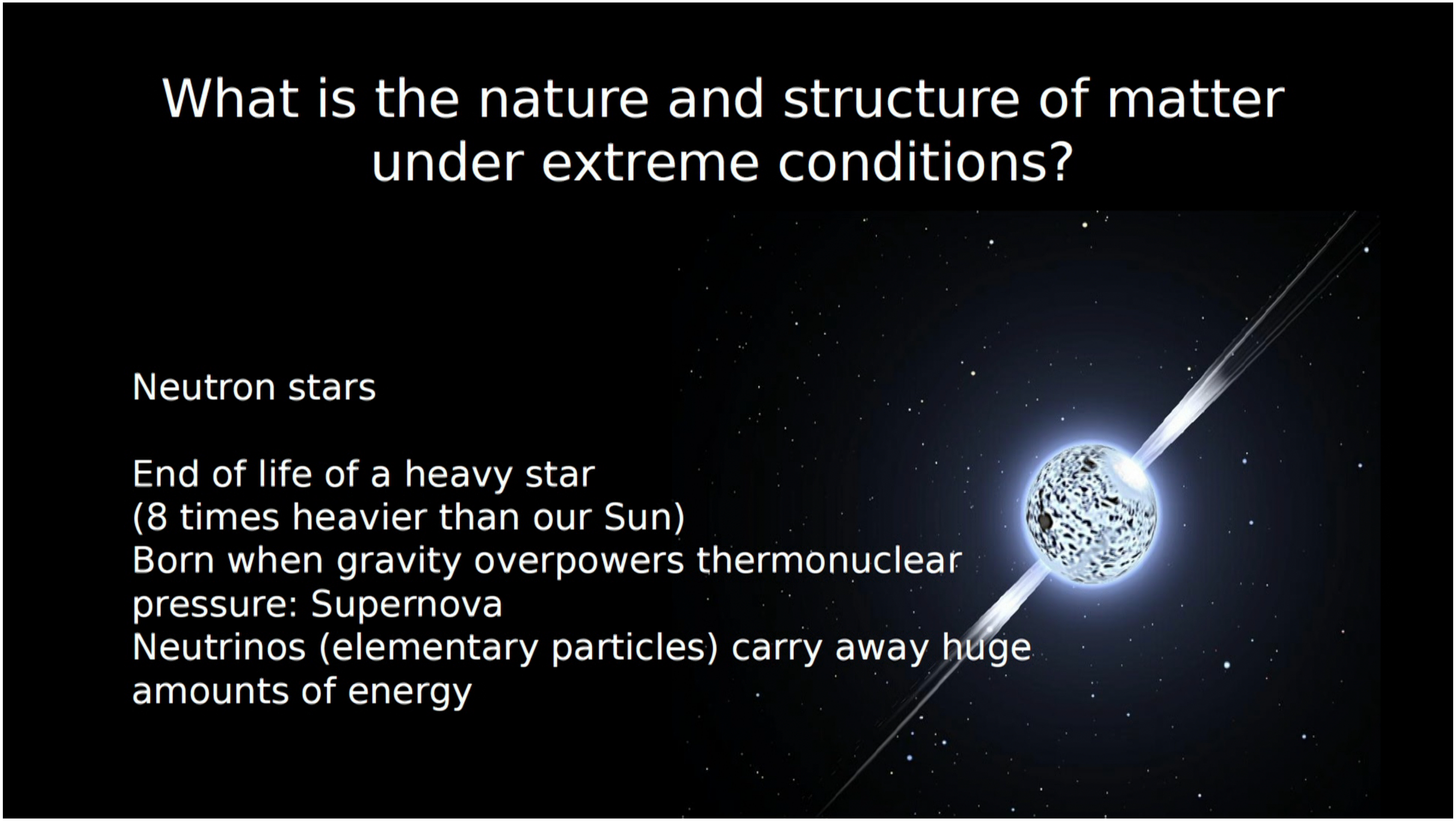




What are the mechanisms of stellar explosions?

Gamma ray bursts (GRB)

Supernovae

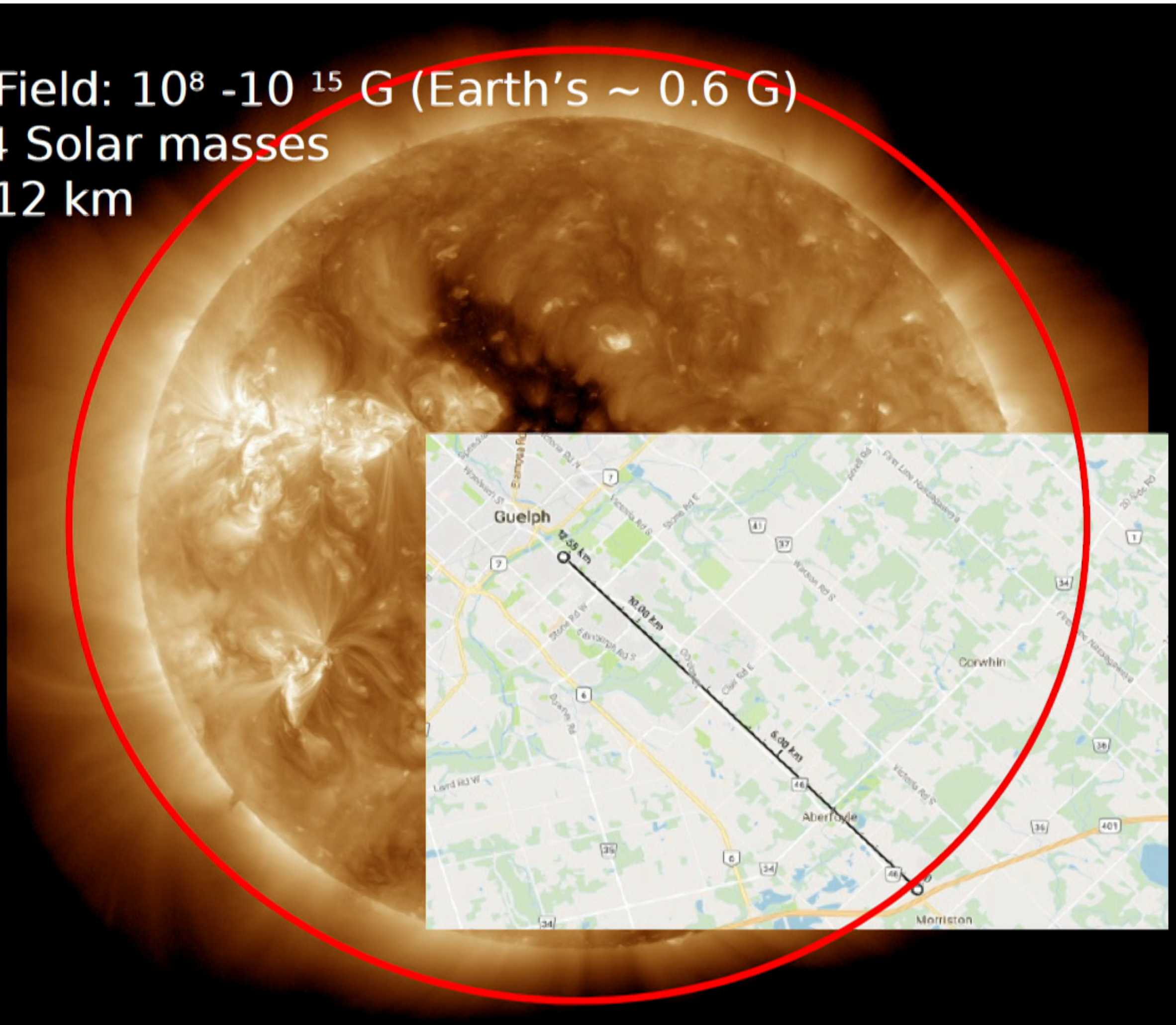


What is the nature and structure of matter under extreme conditions?

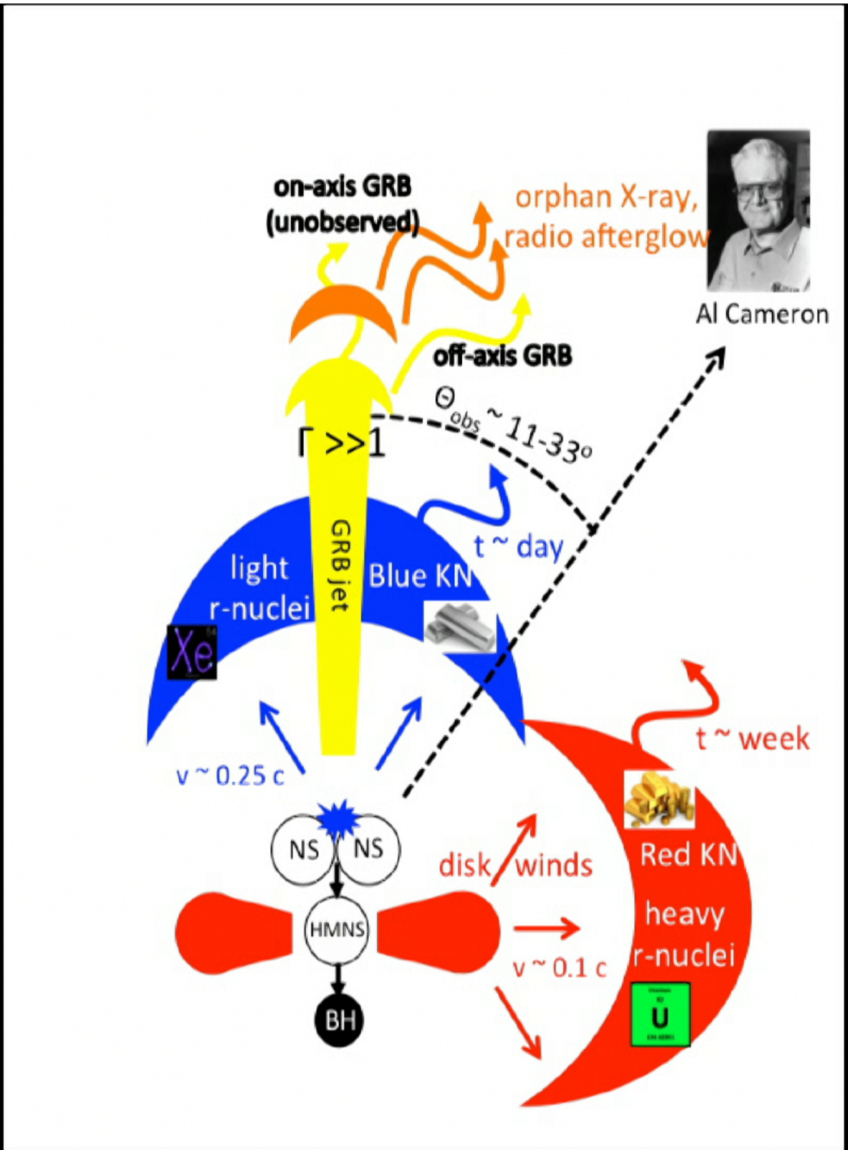
Neutron stars

End of life of a heavy star
(8 times heavier than our Sun)
Born when gravity overpowers thermonuclear pressure: Supernova
Neutrinos (elementary particles) carry away huge amounts of energy

Magnetic Field: 10^8 -10^{15} G (Earth's ~ 0.6 G)
Mass= 1.4 Solar masses
Radius = 12 km

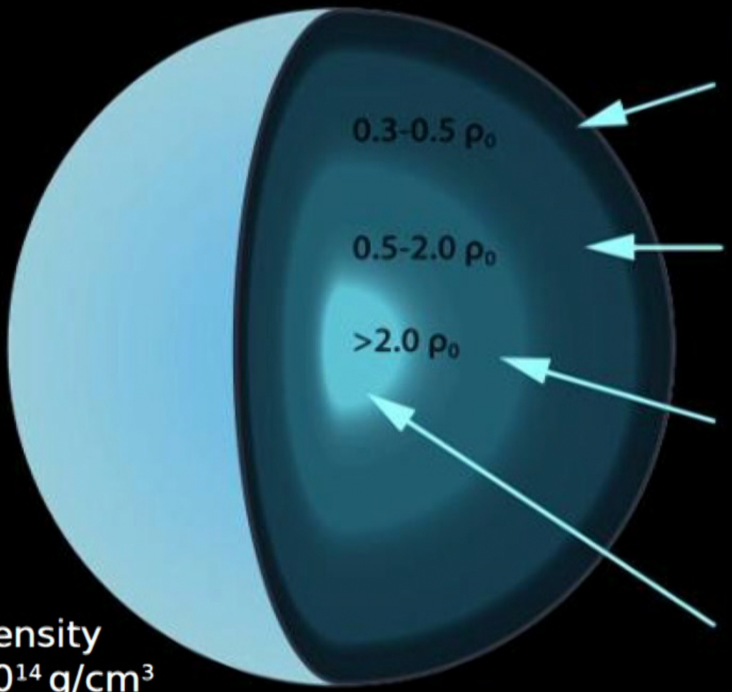


Density: 10^9 to 10^{15} g/cm^3 (lead= 11 g/cm^3, nucleus =2.3×10^{14} g/cm^3)



See B. Metzger (2018)
and ref therein

Neutron star structure



outer crust 0.3-0.5 km

ions, electrons

inner crust 1-2 km

electrons, neutrons, nuclei

outer core ~ 9 km

neutron-proton Fermi liquid

few % electron Fermi gas

inner core 0-3 km

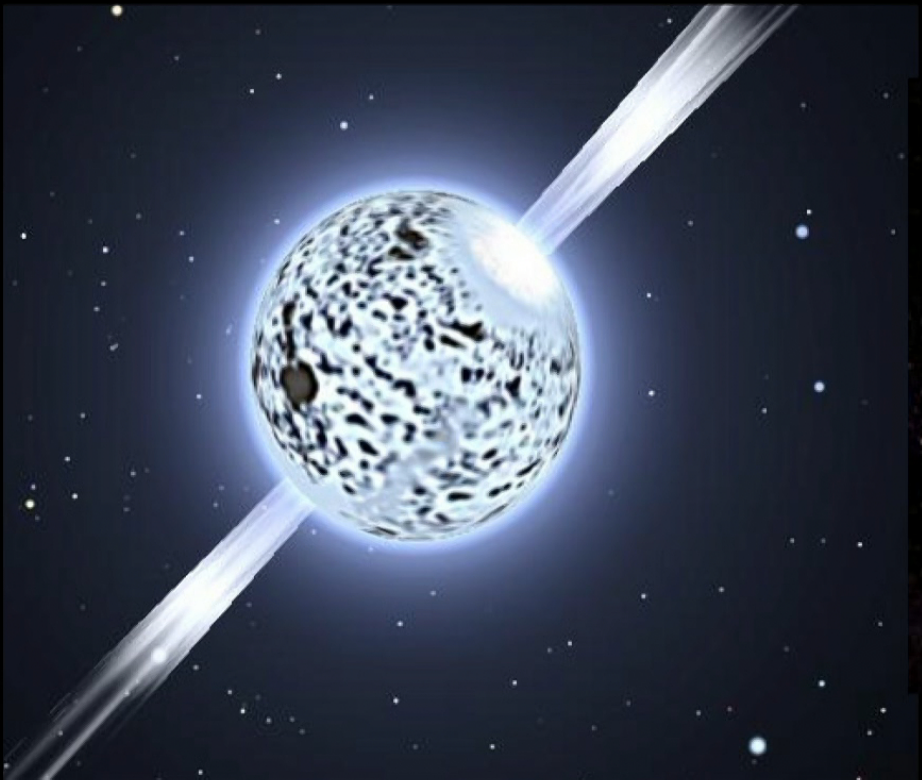
quark gluon plasma

Nuclear density

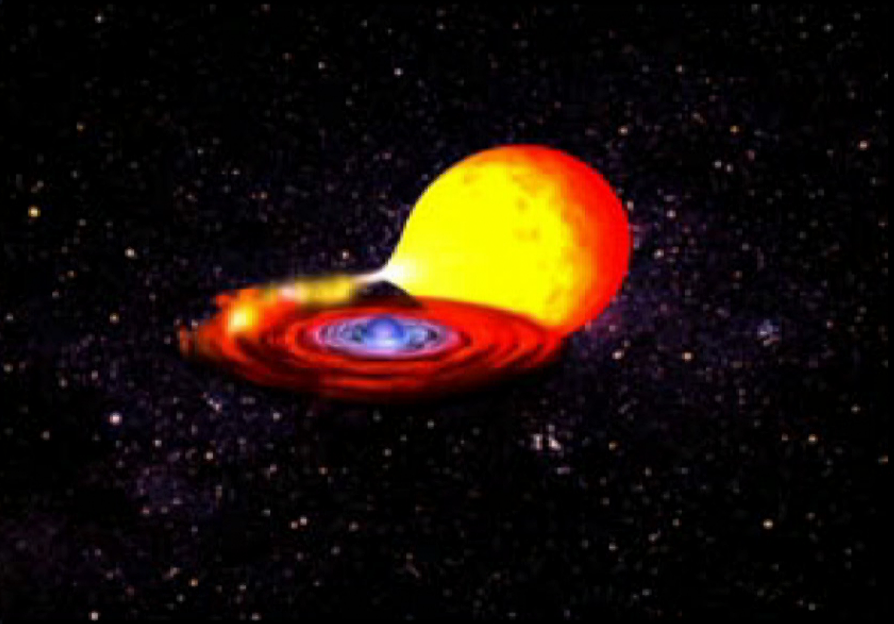
ρ_0=2.3x 10^{14} g/cm^3

Neutron star crust observables

Gravitational Waves



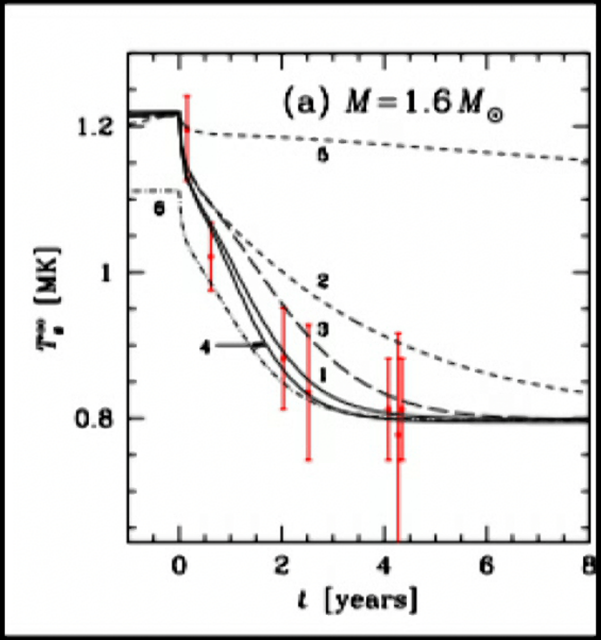
X-ray bursts

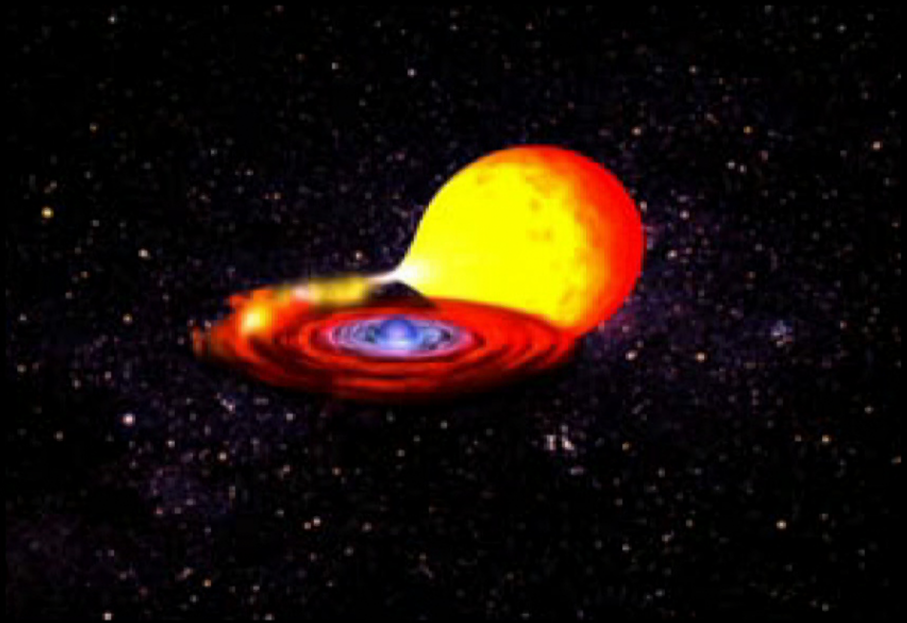


Cooling of accreted Neutron Stars

KS 1731-260

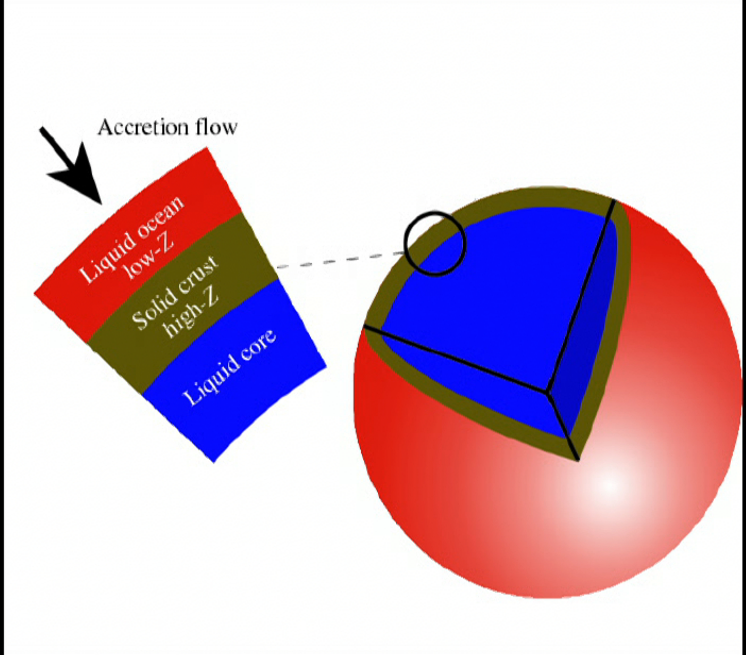
P.S Shternin et al Mon. Not. R. Astron Soc (2007)





Curves 1-4 assume high thermal conductivity (crystal) while 5 low (amorphous)

Simulations of the outer crust



$$v_{ij}(r) = \frac{Z_i Z_j e^2}{r} e^{-r/\lambda_e} ,$$

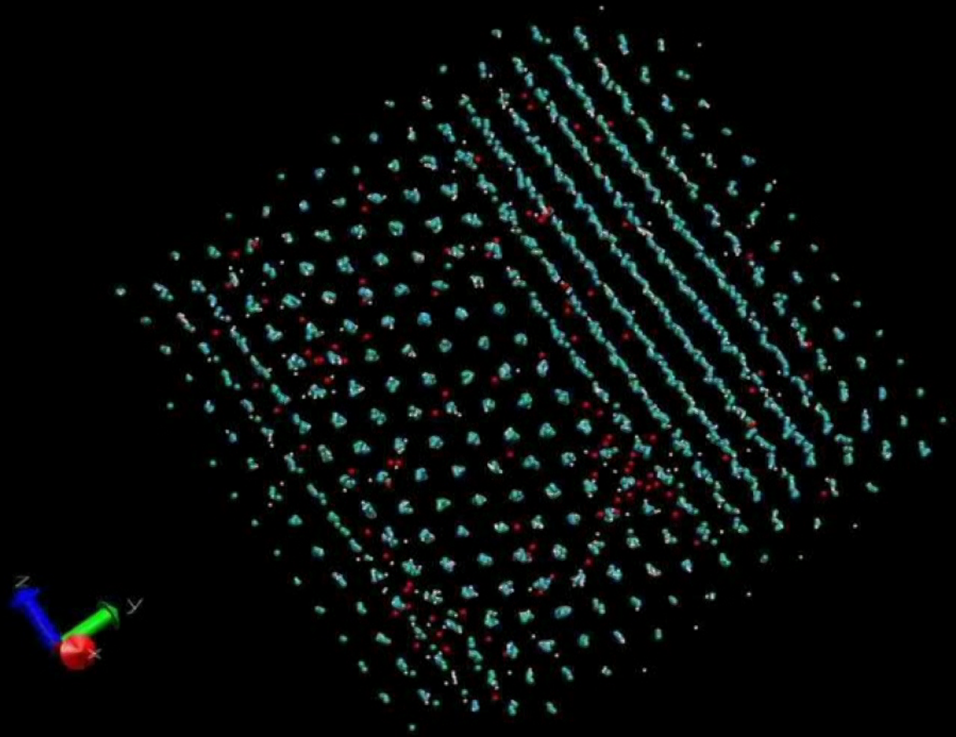
- Degenerated relativistic electrons
- Ions

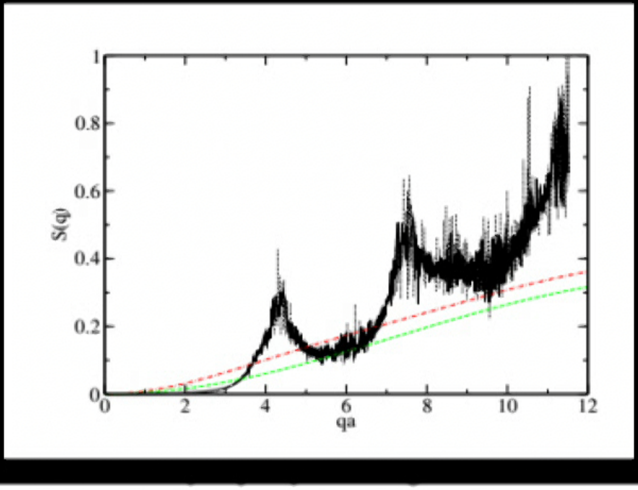
$$S(\mathbf{q}) = \langle \rho^*(\mathbf{q}) \rho(\mathbf{q}) \rangle - |\langle \rho(\mathbf{q}) \rangle|^2 .$$

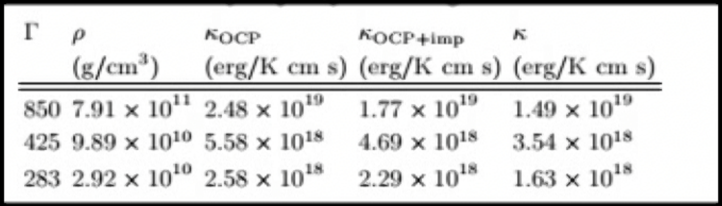
Here the charge density $\rho(\mathbf{q})$ is,

$$\rho(\mathbf{q}) = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} \frac{Z_i}{\langle Z \rangle} e^{i\mathbf{q}\cdot\mathbf{r}_i},$$

Simulations of NS crusts crust







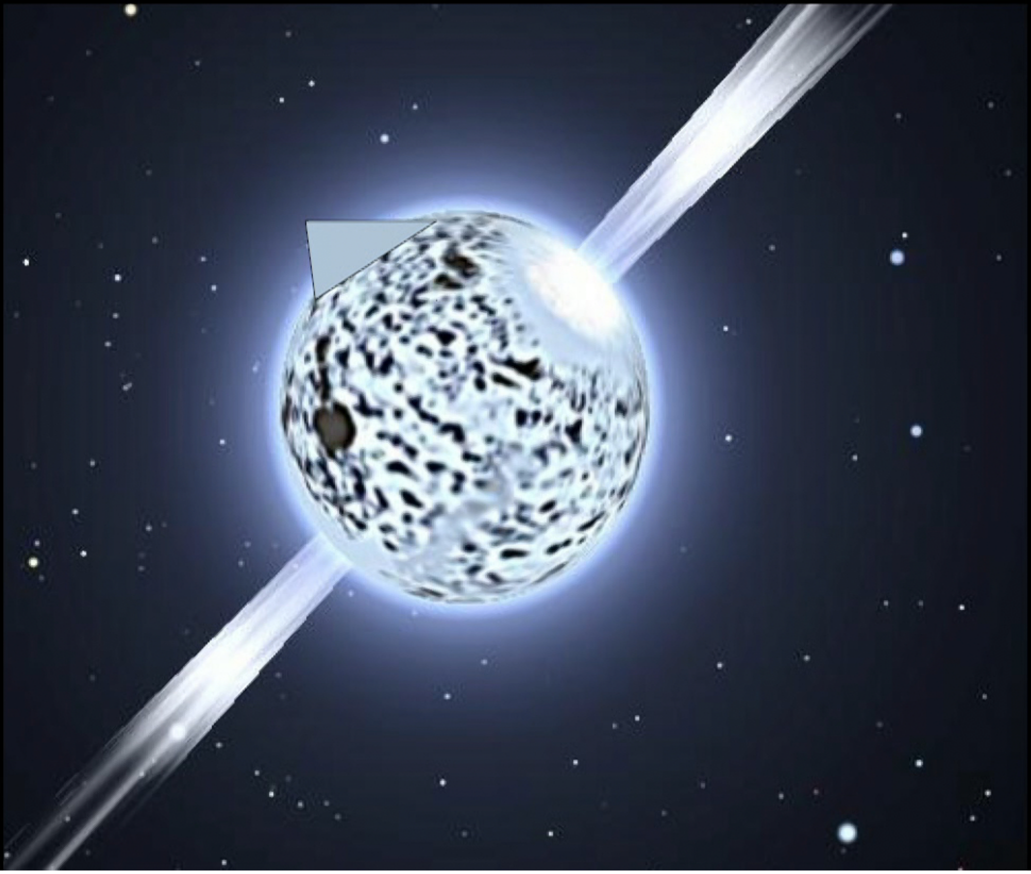
Γ	ρ (g/cm^3)	κ_{OCP} (erg/K cm s)	$\kappa_{OCP+imp}$ (erg/K cm s)	κ (erg/K cm s)
850	7.91×10^{11}	2.48×10^{19}	1.77×10^{19}	1.49×10^{19}
425	9.89×10^{10}	5.58×10^{18}	4.69×10^{18}	3.54×10^{18}
283	2.92×10^{10}	2.58×10^{18}	2.29×10^{18}	1.63×10^{18}

$$\Gamma = \frac{\langle Z^{5/3}\rangle\langle Z\rangle^{1/3}e^2}{aT},$$

- Phase separation: low Z impurities are not uniformly distributed

- C. Horowitz, O. L. Caballero, D. Berry, PRE 2009

Gravitational waves from a deformed NS



$$h_0 = \left(\frac{16\pi^2 G}{c^4}\right)\frac{\epsilon I \nu^2}{d}.$$

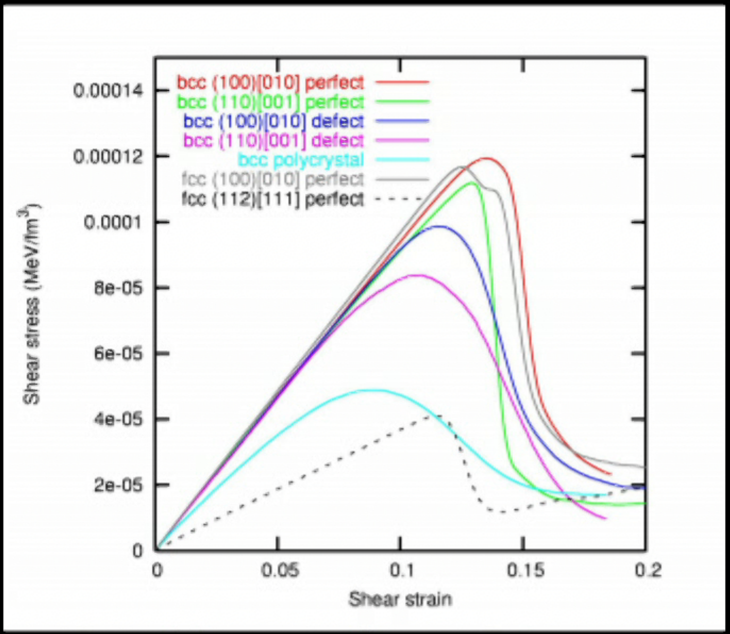
B. Abott Phys.Rev. D76 (2007)

$$\epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}} = \left(\frac{8\pi}{15}\right)^{1/2}\frac{Q_{22}}{I_{zz}},$$

Ellipticity is related to shear modulus μ and breaking strain σ

Ushomirsky et al Mon. Not. R. Astron. Soc (2000)

2 million ions T=0.1 MeV $\rho=10^{13}$ g/cm^3

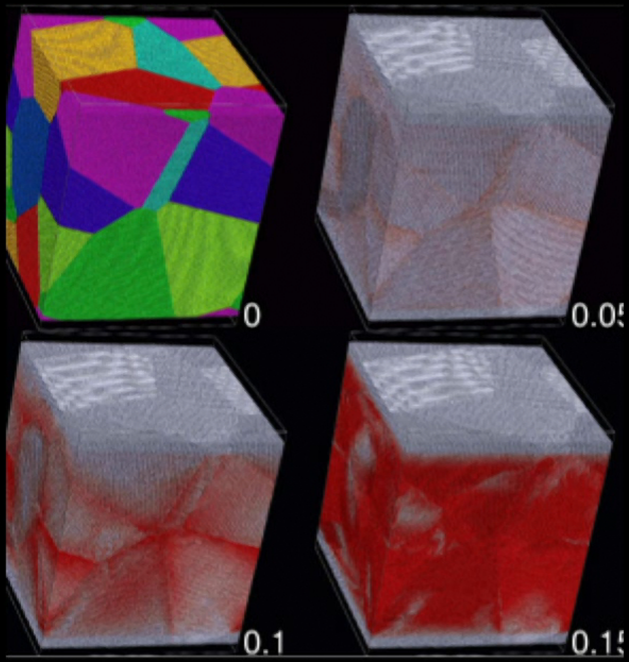


Breaking strain $\sigma=0.1$

$\epsilon=10^{-5} - 10^{-6}$

Upper limits from pulsar $<10^{-8}$

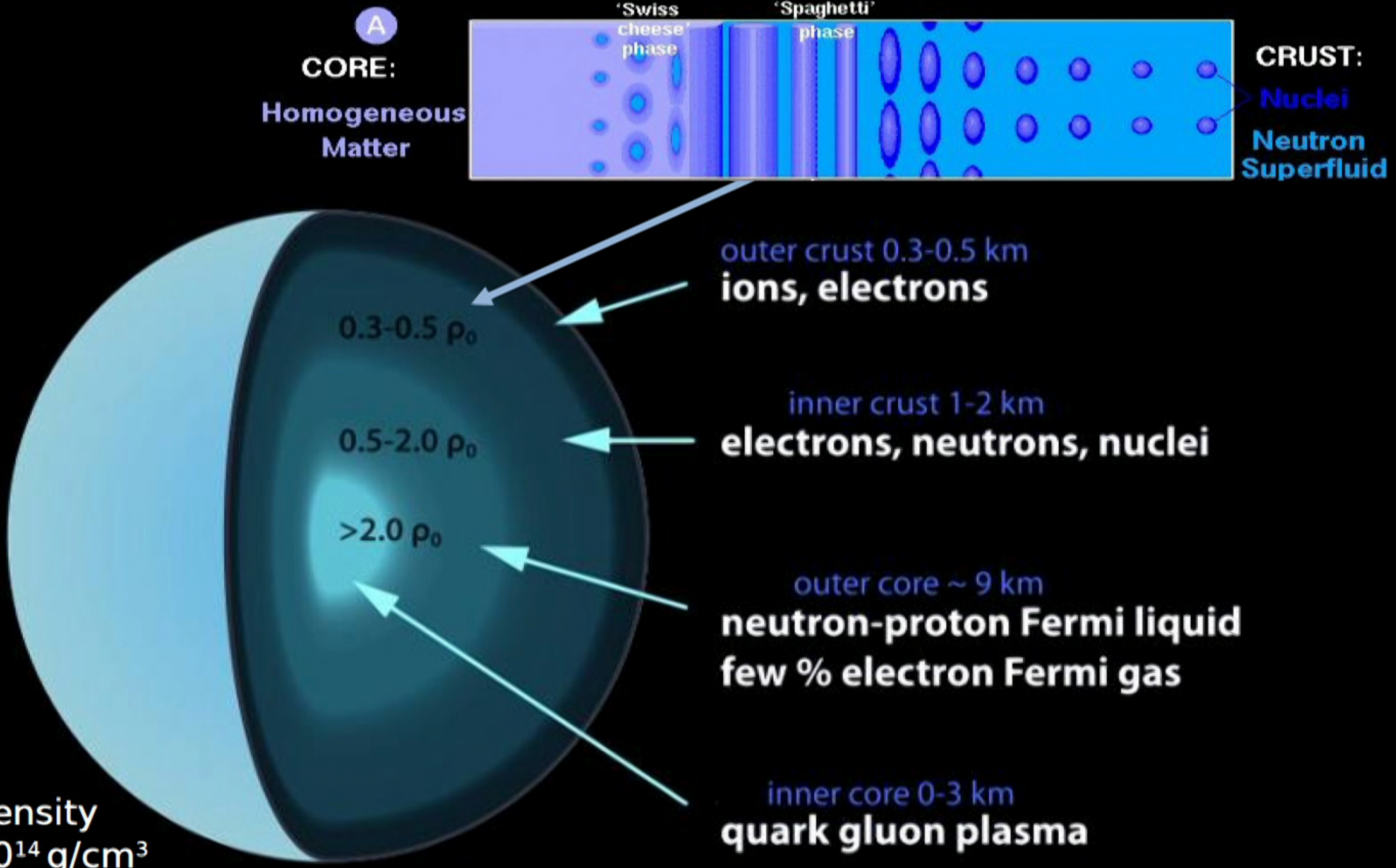
Abott et al 2017



Policrystal fails abruptly in a collective plastic manner rather than yielding at low strains

C. Horowitz & K Kadau PRL (2009)

Neutron star structure



outer crust 0.3-0.5 km
ions, electrons

inner crust 1-2 km
electrons, neutrons, nuclei

outer core ~ 9 km
neutron-proton Fermi liquid
few % electron Fermi gas

inner core 0-3 km
quark gluon plasma

Nuclear density
$\rho_0 = 2.3 \times 10^{14}$ g/cm^3

Simulation of the inner crust: Nuclear Pasta

Frustration

Near saturation density:
Short range attractive nuclear force
Long range repulsive Coul

D. G. Ravenhall, C. J. Pethick, and J. R. Wilson,PRL 50 (1983)

MD simulations C. Horowitz, A. Perez-Garcia, J. Piekarewicz PRC 2004,

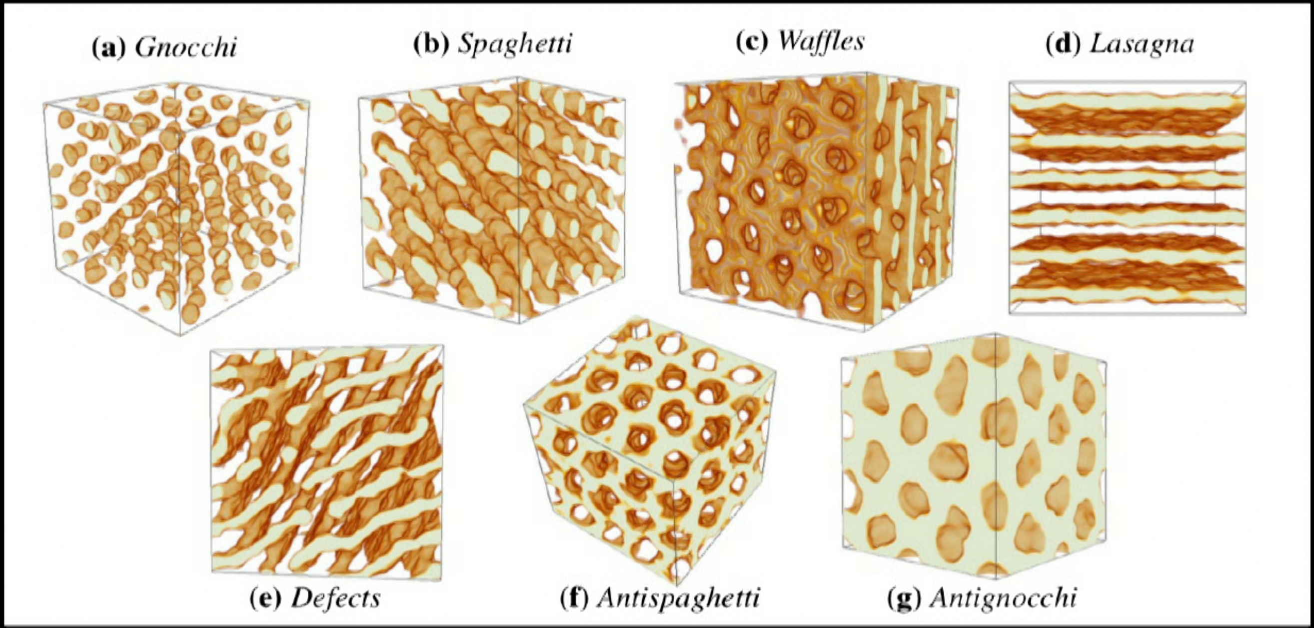
QMD simulations Watanabe et al PRC 2002

HF simulations P. Gogelein and H. Muther PRC 2007

Molecular dynamics simulations: Nuclear Pasta

$$V_{np}(r) = ae^{-r^2/\Lambda} + [b - c]e^{-r^2/2\Lambda}\,,$$
$$V_{nn}(r) = ae^{-r^2/\Lambda} + [b + c]e^{-r^2/2\Lambda}\,,$$
$$V_{pp}(r) = ae^{-r^2/\Lambda} + [b + c]e^{-r^2/2\Lambda} + \frac{\alpha}{r}e^{-r/\lambda}$$

Two-body potentials
a,b,c, Λ are chosen to reproduce eg. binding energies



Caplan & Horowitz, Rev.Mod.Phys. 89 (2017)

Neutrino (related) observables

During mergers and supernovae, the vast majority of energy is released by neutrinos

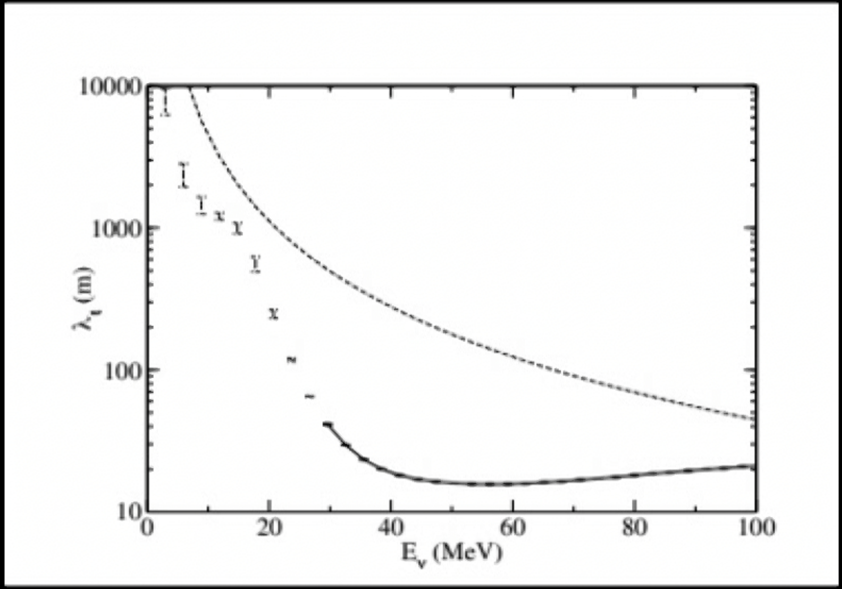
Neutrinos are key in SN explosions, GRB, mergers cooling, nucleosynthesis.

Spectra can be modified by e.g.

- Correlations within the medium (Bacca, Schwenk, Pethick, Raffelt)
- Neutrino oscillations (Balantekin, Fuller, Malkus, McLaughlin)
- Strong gravity

Simulations: Neutrino scattering

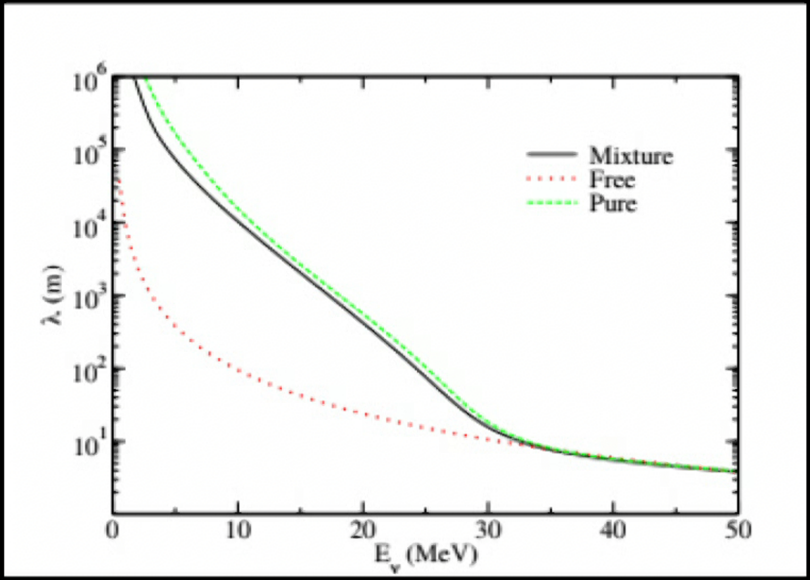
Nuclear Pasta



$\rho = 4\text{x}10^{13}$ g/cm^3, T=1 MeV, Yp=0.2

C. Horowitz, A. Perez-Garcia, J Piekarewicz PRC 2004

Ions



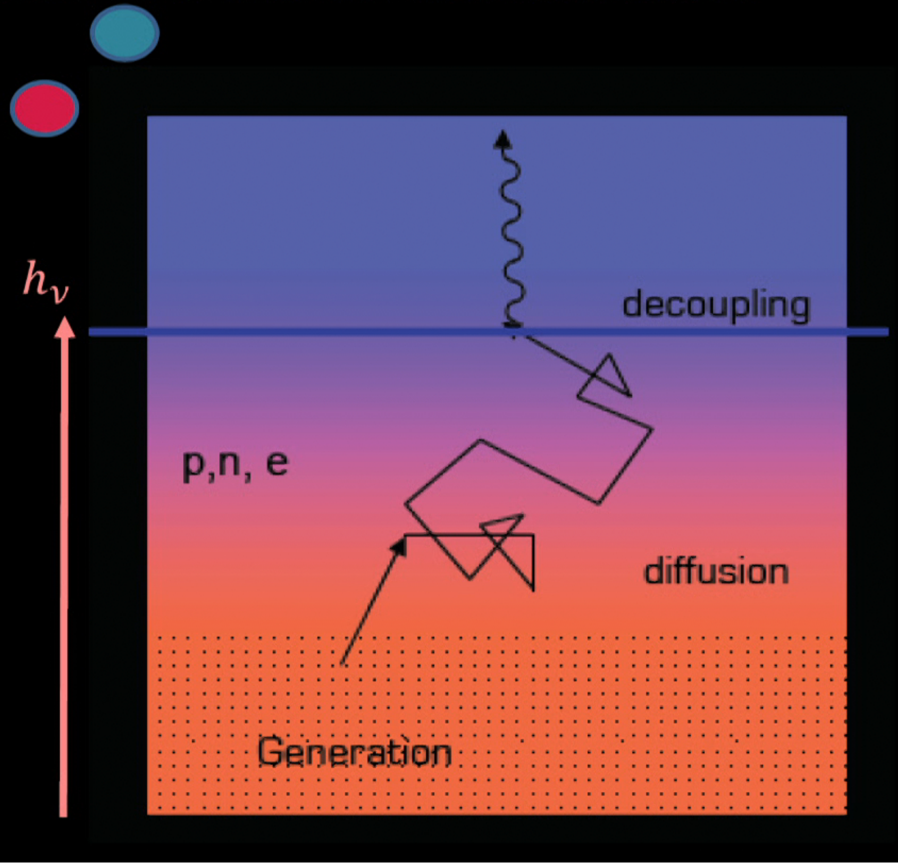
$\rho = 1.66\text{x}10^{13}$ g/cm^3, T=1 MeV, Yp=0.5

O. L. Caballero, C. Horowitz, D. Berry, PRC 2006

Neutrino Surface

At high temperatures (~ 10 MeV) matter is dissociated

ν



$\bar{\nu}_e + p \rightarrow e^+ + n$
$\nu_e + n \rightarrow e + p$
$\nu + \bar{\nu} \rightarrow e + e^+$

Charged Current

$\nu + n \rightarrow \nu + n$
$\nu + p \rightarrow \nu + p$
$\nu + e \rightarrow \nu + e$

Neutral Current (All flavors)

Neutrino detection and EoS

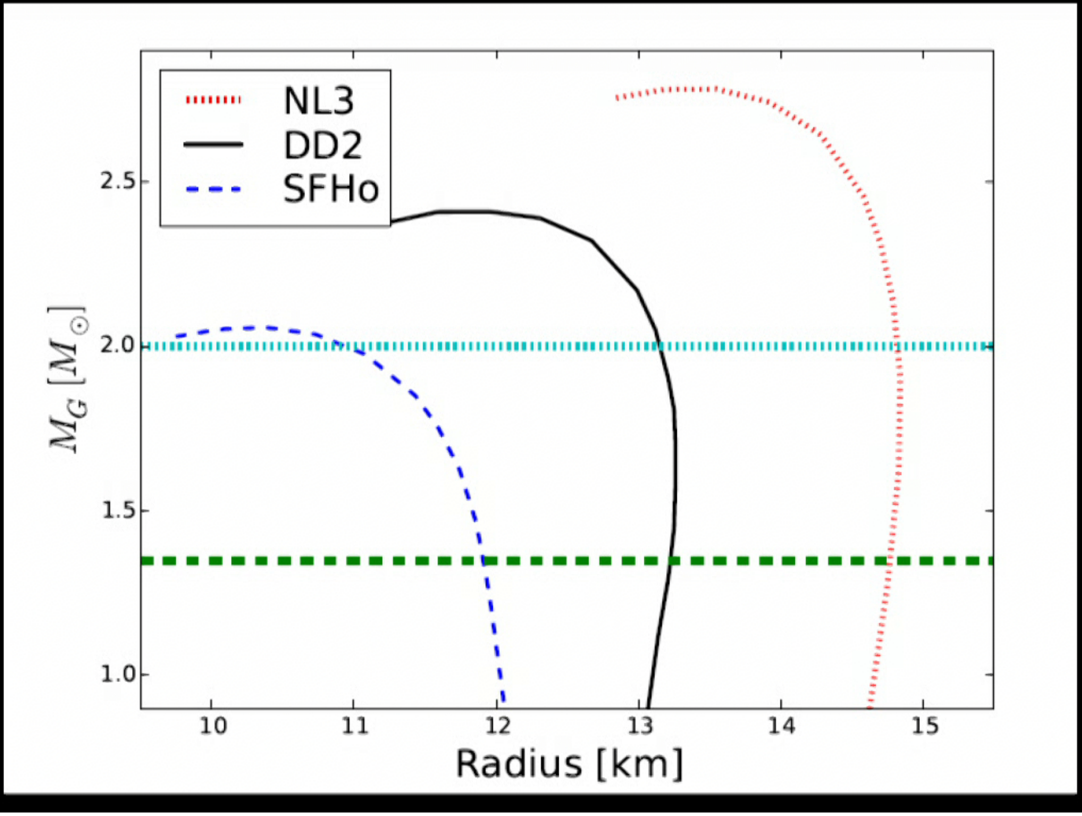
Isolated NS: Equation of State (EOS)

PRD 2015, C. Palenzuela et al PRD 2015

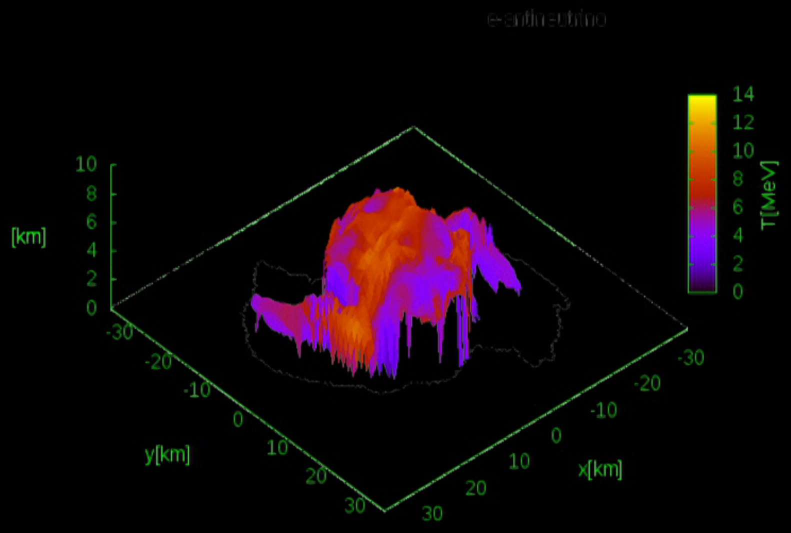
NS mass =1.35 solar masses

Statistical model (Hempel et al 2010) with the Relativistic Mean Field interactions:

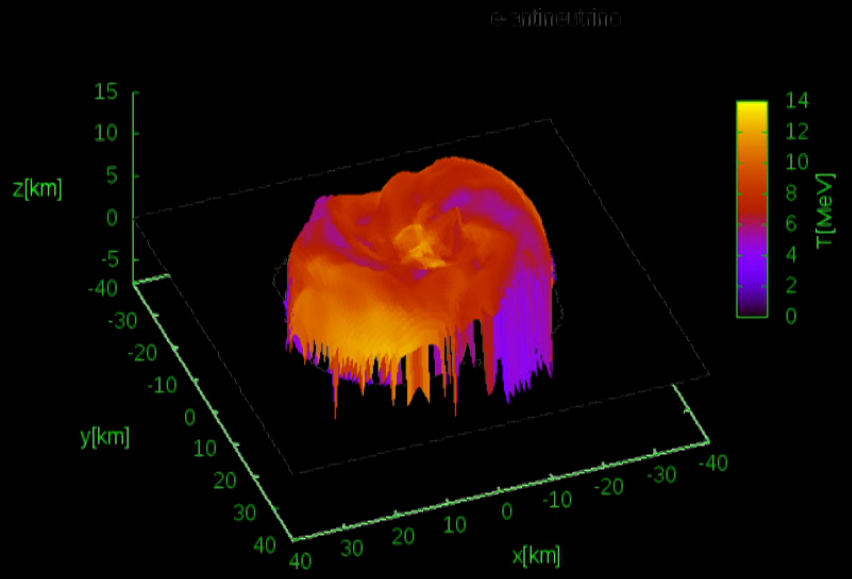
NL3: Lalazissis et al (2008) , stiff
DD2: Typel et al (2012)
SFHo: Steiner et al (2012) , soft



Electron antineutrino surfaces
Equal mass NSs



NL3



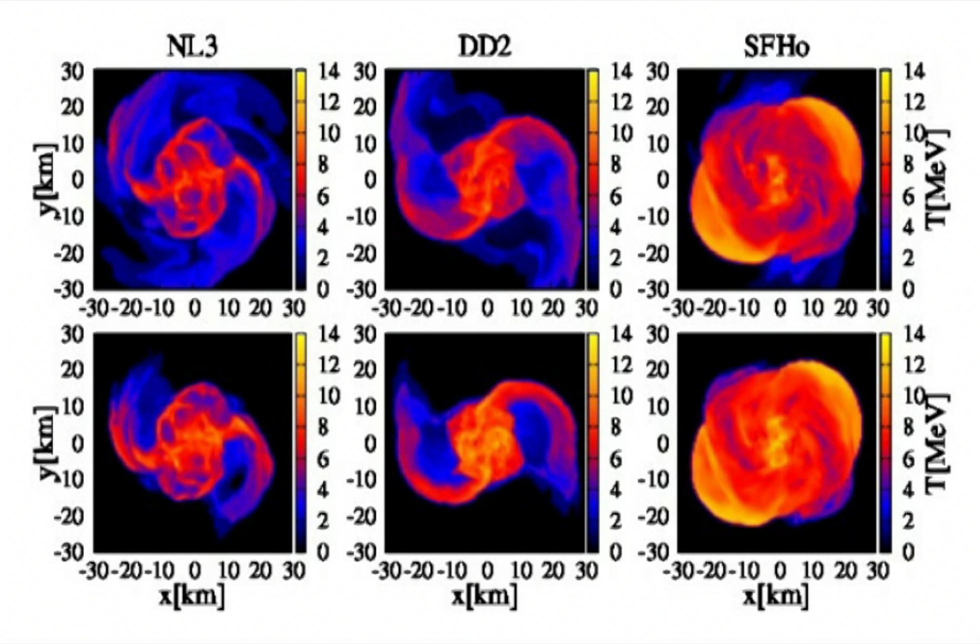
SFHo

Neutrino detection

Fully relativistic 3D merger simulation with neutrino cooling, PRD 2015

e-neutrino

e-antineutrino



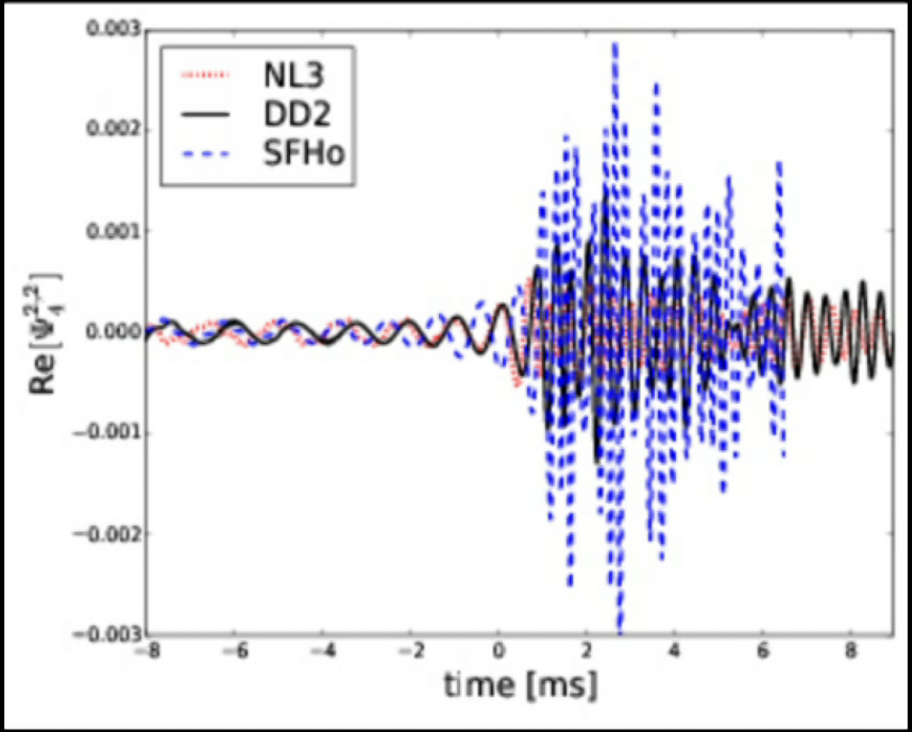
Merger of magnetized NSs in General Relativity with neutrino cooling

C. Palenzuela et al PRD 2015

NS mass =1.35 Solar masses

q=m1/m2=1

NL3: Lalazissis et al (2008) , stiff
DD2: Typel et al (2012)
SFHo: Steiner et al (2013) , soft



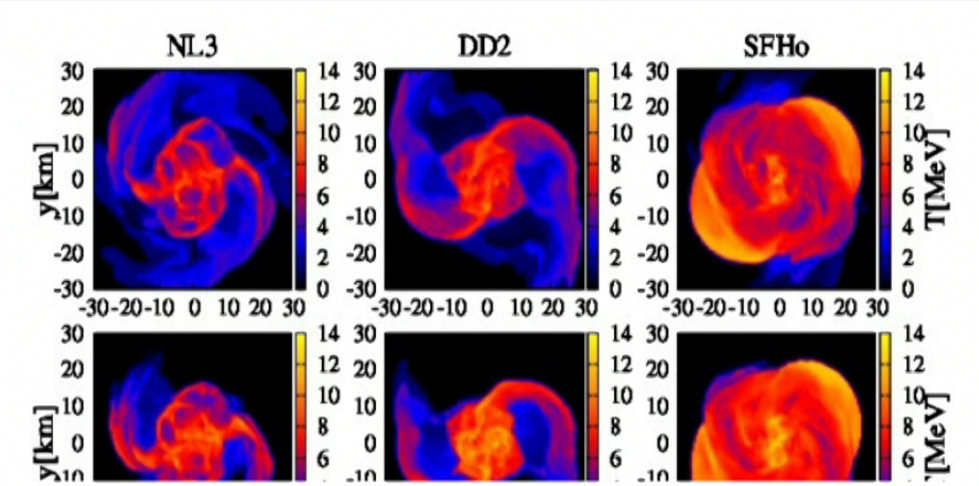
Gravitational wave forms

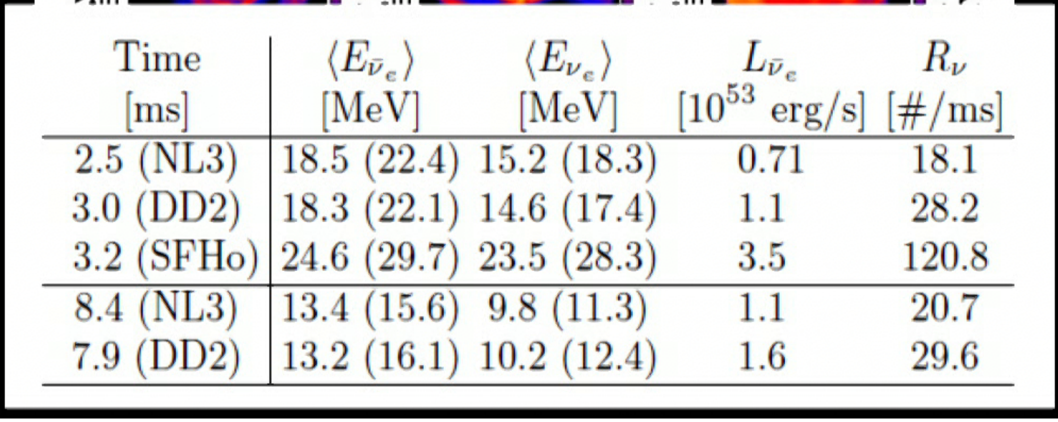
Neutrino detection

Fully relativistic 3D merger simulation with neutrino cooling, PRD 2015

e-neutrino

e-antineutrino





Time [ms]	$\langle E_{\bar{\nu}_e} \rangle$ [MeV]	$\langle E_{\nu_e} \rangle$ [MeV]	$L_{\bar{\nu}_e}$ [10^{53} erg/s]	R_ν [#/ms]
2.5 (NL3)	18.5 (22.4)	15.2 (18.3)	0.71	18.1
3.0 (DD2)	18.3 (22.1)	14.6 (17.4)	1.1	28.2
3.2 (SFHo)	24.6 (29.7)	23.5 (28.3)	3.5	120.8
8.4 (NL3)	13.4 (15.6)	9.8 (11.3)	1.1	20.7
7.9 (DD2)	13.2 (16.1)	10.2 (12.4)	1.6	29.6

Supernova:
R= 1/ms,
L=10^{52} erg/s,
E~ 11 MeV,
t=10 sec

- Neutrinos from mergers will not be mistaken for Supernova neutrinos
-
- Soft EOS would produce a stronger (more energetic and more counts) neutrino signal compared to a stiff EOS.

- We could detect neutrinos from:
  - Milky way and satellite galaxies in SuperK
  - Andromeda (780 kpc) in HyperK

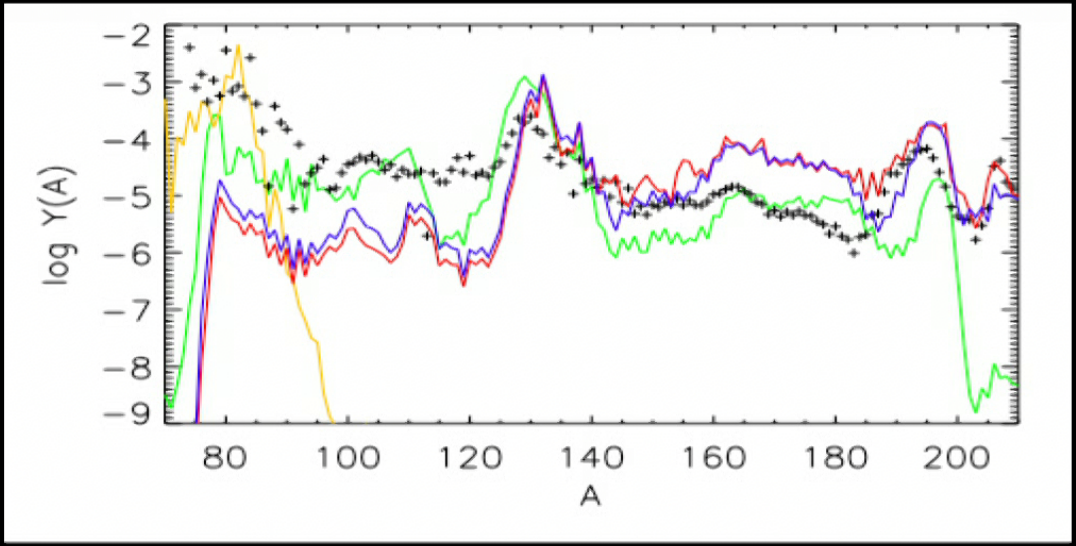
  - Note that the recent NS merger observation lead to a source distance of 40 Mpc.

Accretion-disk nucleosynthesis

Caballero, McLaughlin, Surman. ApJ 2012

Outflow model

- Low entropy S/k=20
- Fast outflow t=5 ms



Yellow = Newtonian neutrinos
Green = Static disk and a=0
Red = Rotating disk and a=0
Blue = Rotating disk and a=0.6

GR neutrinos are less energetic. Material remains neutron rich

No GR: only first peak achieved.

Collaborators

- G. McLaughlin (North Carolina State University), R. Surman (University of Notre Dame)
- Luis Lehner (Perimeter Institute), Carlos Palenzuela (University of the Balearic Islands), David Neilsen (Bringham Young U.), Steve Liebling (Long Island U.), Evan O'Connor (North Carolina State University).
- Chuck Horowitz and D Berry (Indiana University)